



## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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<b>(21) International Application Number:</b> PCT/CA99/00805 <b>(22) International Filing Date:</b> 03 September 1999 (03.09.1999) <b>(30) Priority Data:</b> 2,246,579 03 September 1998 (03.09.1998) CA <b>(60) Parent Application or Grant</b> SIMMONDS, S., Neil [/]; O. SIMMONDS, S., Neil [/]; O. BARRIGAR, Robert, H. ; O.	<b>Published</b>	
<b>(54) Title: BATTERY CHARGER</b> <b>(54) Titre: CHARGEUR D'ACCUMULATEUR</b>		
<b>(57) Abstract</b> <p>A charging circuit and method for charging a lithium-ion cell or battery at a charging voltage that is varied during the charging of the cell or battery from a selected minimum charging voltage to a predetermined maximum charging voltage. The charging circuit includes a transformer for transforming line voltage applied to the primary winding thereof to a lower AC secondary winding voltage, the transformer being selected to limit secondary winding output current when the charging voltage is not less than the selected minimum charging voltage to a value not exceeding a selected upper limit for the lithium-ion cell; a rectifier sub-circuit connected to the secondary winding of the transformer for rectifying the secondary winding voltage; and a charge-voltage regulator sub-circuit connected to the rectifier sub-circuit for receiving the rectified secondary winding voltage and providing an output charging voltage that is limited to the predetermined maximum charging voltage.</p> <b>(57) Abrégé</b> <p>L'invention porte sur un circuit de charge et sur un procédé visant à charger une pile ou accumulateur aux ions de lithium à une tension de charge variant d'une tension minimale sélectionnée à une tension maximale prédéterminée. Le circuit de charge comprend un transformateur qui transforme la tension du secteur appliquée sur l'enroulement primaire en une tension de courant alternatif inférieure appliquée sur l'enroulement secondaire. Le transformateur est sélectionné de façon à limiter le courant de sortie de l'enroulement secondaire lorsque la tension de charge n'est pas inférieure à la tension de charge minimale sélectionnée par rapport à une valeur n'excédant pas une limite supérieure sélectionnée de la pile aux ions de lithium. Un sous-circuit de redressement est connecté à l'enroulement secondaire du transformateur de façon à redresser la tension de l'enroulement secondaire, et un sous-circuit de régulation de la tension de charge est connecté au sous-circuit de redressement de façon à recevoir la tension redressée de l'enroulement secondaire et à générer une tension de charge de sortie limitée à la tension de charge maximale prédéterminée.</p>		

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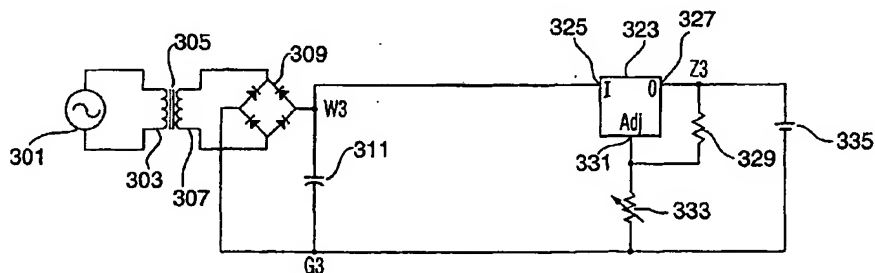
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(54) Title: BATTERY CHARGER



(57) Abstract

A charging circuit and method for charging a lithium-ion cell or battery at a charging voltage that is varied during the charging of the cell or battery from a selected minimum charging voltage to a predetermined maximum charging voltage. The charging circuit includes a transformer for transforming line voltage applied to the primary winding thereof to a lower AC secondary winding voltage, the transformer being selected to limit secondary winding output current when the charging voltage is not less than the selected minimum charging voltage to a value not exceeding a selected upper limit for the lithium-ion cell; a rectifier sub-circuit connected to the secondary winding of the transformer for rectifying the secondary winding voltage; and a charge-voltage regulator sub-circuit connected to the rectifier sub-circuit for receiving the rectified secondary winding voltage and providing an output charging voltage that is limited to the predetermined maximum charging voltage.

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## Description

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## BATTERY CHARGER

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## 5 Field of the Invention:

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This invention relates to the field of devices and methods for charging lithium-ion cells (or batteries) and specifically to a charging circuit including a power transformer in which the loading curve of the power transformer is used to limit the current flow to the lithium-ion cell (or battery) and a method for charging lithium-ion cells (or batteries) in which the loading curve of a power transformer is used to limit the current flow to the lithium-ion cell (or battery).

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## Background of the Invention:

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Lithium-ion cells are used in battery packs where high energy density and low weight are required. However, lithium-ion cells can be dangerous if operated outside of their rated specifications. Typically, such batteries are used in controlled environments and are accompanied by suitable protective devices to prevent such problems as short circuits, unduly high temperatures and over-discharge. A number of such protective devices are typically installed in the battery pack. It is standard industry practice that lithium-ion cells are equipped with in-pack circuitry that provides the necessary protection for the cell in use. Although the in-pack circuitry will provide over-all protection, suitable cell charging circuitry is required to provide repeated charging of the cell while satisfying applicable charging and operational constraints that vary

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- 1 -

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5 somewhat from one cell type to another, as the manufacturer may  
have specified for any given design.

10 Particularly, lithium-ion cells carry a risk of generating  
5 excess gas due to overcharge or overdischarge - this may cause  
the safety vent of the battery pack to open and release  
electrolyte into the atmosphere. If this release of electrolyte  
15 is continued, the cells can lose sufficient electrolyte that they  
are disabled. Further, overcharge or overdischarge may generate  
10 excess heat, causing a severe rise in temperature that can reduce  
the ability of the cell to retain energy and reduce the number  
20 of charging cycles the cell can undergo before it must be  
replaced. More seriously, overcharging or overdischarging may  
occur to such an extent that the lithium metal is isolated from  
25 the other elements and may become plated onto one of the  
electrodes. Lithium metal is explosive in water and will, in  
varying degrees, react with the moisture in the atmosphere.  
30 Lithium-containing batteries have been known to catch fire,  
although more recent safety designs have reduced the chances of  
20 this occurrence. The avoidance of overcharge voltage and  
overcharge current during charging of a lithium-ion cell is  
35 therefore an important objective in the use of lithium-ion cells,  
has been achieved by a number of known regulator circuits, and  
is also a principal objective of the present invention.

40 25 It is known that the attained charge capacity of a lithium-  
ion cell is significantly reduced if the charging voltage is less  
45 than the manufacturer's recommended maximum charging voltage (say  
4.1 volts). With a drop of charging voltage of only 0.05V  
30 (approximately 1%), a loss of up to 5% in charge capacity occurs.  
However, if the charging voltage reaches only 4.0 volts (a drop

5 of 0.1V or approximately 2%) then a loss of charge capacity of  
up to 12% occurs. On the other hand, as pointed out previously,  
if one exceeds the manufacturer's recommended maximum charging  
10 voltage, the life cycle of the cell is decreased, or worse,  
5 catastrophic breakdown of the cell can occur. Therefore one is  
compelled by these combined constraints to charge the lithium-ion  
cell at a voltage (at least at the end of the charging cycle)  
15 that is as close as reasonably possible to the maximum charging  
voltage without exceeding it.

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20 Previous battery charging circuits for lithium-ion cells or  
batteries are known that include suitable regulator devices to  
maintain charging voltage and current within acceptable  
constraints. The "charge inhibition voltage" refers to the value  
25 that the cell manufacturer has set as the upper limit of  
operating/charging voltage of the cell. If the voltage exceeds  
this value, lithium metal may become plated to an electrode, with  
30 potentially dire consequences as discussed above. The "maximum  
charging voltage" is also established by the manufacturer at a  
20 lower value than the charge inhibition voltage; if for example  
the charge inhibition voltage is 4.35 volts for a representative  
35 cell, the maximum charging voltage is typically set at about 4.1  
or 4.2 volts. Lithium-ion cell manufacturers have found that  
operation above the maximum charging voltage tends to reduce  
40 severely the recharging life cycle of the battery. Accordingly,  
25 in order to ensure that charging voltage is no greater than the  
set maximum charging voltage for the cell, controlled lithium-ion  
cell charging circuits typically provide a maximum output charge  
45 voltage that is no more than the maximum charging voltage.

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5 In a typical charging circuit, an alternating current source  
operating at line voltage (typically 110-120 volts in North  
America) is applied to the primary winding of a transformer whose  
10 secondary winding applies a relatively low AC voltage to a bridge  
5 rectifier. The output of the bridge rectifier is applied across  
a smoothing capacitor to the load (the load in the charging  
circuit is the lithium-ion cell or battery to be charged). If  
15 no circuit elements were present other than the foregoing, the  
output voltage delivered to the lithium-ion cell would be at risk  
10 of exceeding the maximum charging voltage and ultimately might  
exceed the charge inhibition voltage of the lithium-ion cell.  
20 Accordingly, interposed between the bridge circuit and the  
lithium-ion cell or battery is a regulator circuit for limiting  
the voltage and current applied to the lithium-ion cell or  
25 battery during the charging operation.

30 Two types of regulator circuit are conventionally used, both  
of which are constant current/constant voltage regulator  
circuits, viz a linear regulator circuit, and a switching  
20 regulator circuit.

35 A switching regulator circuit includes a specially-designed  
charge control integrated circuit (IC) device for use with the  
other circuit elements. Such IC device is connected within the  
40 25 switching regulator circuit in constant-current mode. With the  
regulator operating in constant-current mode, charging continues  
at a constant current until the voltage across the lithium-ion  
cell or battery reaches the pre-set maximum charging voltage.  
45 The circuit then limits the output charging voltage to the  
30 maximum charging voltage, using a pulse-width modulation  
technique. According to this technique, the length of time that



charge current is applied to the lithium-ion cell load during each AC cycle is progressively and gradually decreased as charging proceeds.

The commercially available Benchmarq™ model bq2054 IC device and the 4C™ Technologies 4C-101656Li device are representative examples of charge control IC elements for use with a switching regulator circuit of the type described above.

As an alternative to the switching regulator, the principal other previously known regulated lithium-ion cell charging circuit includes a linear regulator incorporating a pair of suitable linear regulator charge control IC devices, one such device being connected within a charge current regulation subcircuit of the overall charging circuit, and the other within a charge voltage regulation subcircuit. These linear IC devices incorporate transistors constrained to operate within a relatively linear region of operation which happens to be a relatively inefficient region of operation. (By contrast, switching regulator IC devices permit the transistors in the integrated circuit to operate in relatively efficient Class C mode of operation.) Until fairly recently, such linear regulator circuits were considerably less efficient than switching regulator circuits, and generated an undesirable amount of heat, although such linear regulators were typically lower in cost than switching regulators. For the older type of linear regulator, the minimum differential voltage (generally referred to as the "minimum dropout voltage") between unregulated voltage at the input of the linear regulator circuit and the regulated output charge voltage of the linear regulator circuit was approximately 1.5 volts when used for constant-voltage regulation and 1.2 volts

5 when used for constant-current regulation. As this differential  
voltage is relatively high, leading to relatively inefficient  
charging, linear regulators using the older type of linear  
10 regulator IC device were typically used only for low-power  
5 charging requirements.

15 A previously known battery-charging circuit not designed  
specifically for lithium-ion cells or batteries that uses only  
a single linear regulator charge control IC device that provides  
10 both charge current regulation and voltage regulation is shown  
20 in Figure 11-2 of Gordon McComb, *Robot Builder's Bonanza* (New  
York, 1987), p. 81. However, that circuit includes a current  
limiting resistor and a silicon-controlled rectifier and appears  
25 to be designed to provide constant charging current until the  
15 charging voltage reaches the maximum charging voltage.

30 More recently, a new generation of linear regulator charge  
control IC devices has been developed that offers significant  
improvements in efficiency and a reduction in heat generation.  
20 These new regulators are frequently referred to as low drop-out  
voltage regulators or "LDO" regulators, because the minimum  
35 differential voltage (dropout voltage) between input supply  
voltage and output charge voltage can be as low as about 0.5  
volts when used for constant-voltage regulation and as low as 1.2  
40 25 volts (about the same as for the older type of linear regulator  
IC device) when used for constant-current regulation of the  
charging circuit. The 0.5-volt differential when the IC device  
45 is operated in constant-voltage mode permits these LDO regulators  
to operate from an unregulated DC supply voltage that is  
30 appreciably closer to the maximum charging voltage than was the

5 case for the older linear regulator IC devices, thereby reducing power dissipation.

10 The older type of linear regulator charge control IC device  
5 is exemplified by the Motorola™ LM317 IC device. The more recently available LDO linear regulator charge control IC device is exemplified by the Micrel™ MIC29372 IC device.

15 Despite the improvements effected in IC design, lithium-ion  
10 cell charging circuits of the types previously known remain inherently inefficient because they operate from unregulated DC  
20 power that is supplied at a voltage significantly above the maximum charging voltage; the inefficiencies are also due to the conventional use of both charge current and charge voltage  
25 regulating subcircuits, both of which dissipate energy.

30 The prior art teaches that both charge current and charge voltage should be actively regulated during the charging of lithium-ion cell; the charge current initially at a constant  
20 value until the charge voltage reaches the manufacturer's suggested maximum charging voltage and the charging voltage at  
35 the maximum charging voltage thereafter. Actively regulating current to a constant value requires that the regulating subcircuit be supplied with a high enough voltage that the  
40 25 regulator will not drop out of regulation as the charging voltage increases to the maximum charging voltage.

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## Summary of the Invention:

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The conventional design approach heretofore taken for the design of the regulation of lithium-ion cell or battery charging circuits proceeds on the premise that it is a good idea for the regulating circuit to be constantly active and to be regulating charging voltage and/or charging current throughout the complete cell charging process. (Herein frequent reference will be made to the "cell" to be charged, it being understood that with appropriate adjustments, one may in each case charge a battery of cells. Generally, a reference to a "battery" should be understood to include a reference to a single cell.)

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According to the invention, the transformer used in the lithium-ion charging circuit is selected so that its inherent current-limiting characteristic (loading effect) permits the circuit to charge the lithium-ion cell during an initial period in which the regulator circuit need not perform any regulating function. This enables a satisfactory regulator circuit to be designed according to the invention using only a single charge control IC device that in an initial stage of the charging operation is in non-regulating mode, permitting the rectified transformer secondary output to be applied to the lithium-ion cell with only a minimum voltage drop across the single IC device (present in a voltage regulating subcircuit), as compared to two voltage drops across two IC devices (one in a current-regulating subcircuit and one in a voltage-regulating subcircuit) that would be present in conventional charging circuits, thereby affording substantial energy savings. When the charge voltage reaches a pre-set threshold level, the regulator circuit functions for the

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5 remainder of the charging operation in a manner similar to that  
of previous voltage regulation subcircuits, but with less overall  
power loss, since there is no separate current-regulation  
10 subcircuit present.

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Accordingly, the invention provides a charging circuit for  
a lithium-ion cell (or battery) including a selected suitable  
15 transformer characterized by an inherent secondary output  
current-limiting capability that meets the initial current-  
limiting needs of the charging circuit, in combination with a  
20 suitable rectifier circuit (that may itself be of conventional  
design) and a linear charge-voltage regulating subcircuit that  
during the initial part of the charge cycle does not operate in  
regulating mode. Otherwise the linear charge-voltage regulator  
25 subcircuit and the rest of the circuit may be of conventional  
design, except that no separate charge-current regulator  
subcircuit is necessary nor present, thereby avoiding the  
associated power dissipation that occurs in such subcircuit  
30 present in conventional designs.

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During the initial stage of the charging operation, charge  
35 voltage and charge current are maintained within acceptable  
limits by the condition of the discharged lithium-ion cell and  
the inherent secondary winding current-limiting characteristic  
40 25 of the transformer itself, and therefore the linear charge-  
voltage regulating subcircuit drops the supply voltage only by  
a minimum voltage drop (the minimum dropout voltage) between the  
rectified transformer secondary output and the lithium-ion cell  
45 being charged. The charge current applied during this initial  
30 stage slowly declines as the voltage across the cell being  
charged increases. For that reason, this initial mode of

5 operation of the charging circuit may be referred to as "taper  
current mode", since the current tapers off from an initial value  
varying more or less linearly with time to a reduced value.  
10 During the later stage of the charging operation, the linear  
5 charge-voltage regulating subcircuit operates in the same manner  
as a conventional such subcircuit to limit applied charge voltage  
to the maximum charging voltage, during which time charge current  
15 decreases substantially logarithmically in the same manner as  
would occur in a conventional charging circuit incorporating  
10 linear regulation. Preferably the linear regulator IC device  
used in the charge-voltage regulating subcircuit is of the LDO  
20 type for maximum efficiency and charge capacity.

The inventor has found that the charge-current regulator  
25 15 subcircuit and the consequent power dissipation associated with  
such subcircuit may be eliminated without significantly affecting  
the performance of the battery charger while maintaining the  
charging voltage within safe limits. The elimination of the  
30 current-limiting subcircuit offers both improved energy  
20 efficiency and reduced cost of manufacture of the charging  
circuit, because not only is one subcircuit eliminated, but the  
35 required transformer can be smaller and lighter.

Note that it is important that the current rating and  
40 25 secondary voltage of the transformer be carefully selected, both  
to prevent damage to the cell during the initial charging stage  
and to provide an appropriate transformer loading curve so that  
the supply voltage begins to be regulated after the desired  
45 portion of the charging cycle has been completed. Specifically,  
30 a current rating for the transformer should be selected that is  
not greater than the maximum charging current for the cell or

5 battery suggested by the manufacturer. The secondary voltage of  
the transformer (and therefore the characteristics of the  
transformer loading curve) should then be selected so that when  
10 the maximum charging current is flowing through the secondary  
5 winding of the transformer, the voltage supplied to the voltage  
regulating subcircuit is approximately equal to the sum of (1)  
a minimum charging voltage of the cell or battery to be charged  
15 selected to be somewhat less than the manufacturer's nominal  
voltage rating of the battery and (2) the minimum voltage drop  
10 across the voltage regulating subcircuit. To compensate for line  
voltage variations, it is advisable to select the secondary  
20 voltage of the transformer based upon the maximum expected  
transformer primary voltage, rather than upon the average primary  
voltage, to avoid having the current flow during the initial  
25 charging stage exceed the transformer rating due to higher than  
average primary voltage.

30 A minimum charging voltage somewhat less than the nominal  
voltage is desirable, although the exact voltage used is not  
20 critical. For example, the battery manufacturer's specifications  
for the battery for which the charge is being designed should  
35 provide the charging voltage as a function of time, assuming  
constant current until the charging voltage rises to the maximum  
charging voltage. In typical batteries known to the inventor,  
40 25 the charging voltage increases almost instantly from the  
discharged voltage (which may be as low as 2.5 volts) to  
approximately 3.3 to 3.7 volts reaching roughly 3.6 to 3.9 volts  
within a few minutes, depending upon a number of factors  
45 including the age and prior use of the battery. After the first  
30 few minutes the charging voltage continues to climb, but somewhat  
more slowly, until it reaches the maximum charging voltage of 4.1

5 or 4.2 volts as specified by the manufacturer (at which point the  
charging circuit must clamp the voltage or the battery may be  
10 damaged). While an initial charging voltage of 3.4 volts or even  
5 less could be used, the inventor has found that using an initial  
charging voltage of 3.5 to 3.6 volts to select the current rating  
of the transformer does not cause the charging current during the  
15 first few minutes under charge to reach levels high enough to  
adversely affect the battery being charged.

10 In accordance with the invention, for given battery  
specifications, the transformer selected for the charger will  
20 have a lower power rating (a lower current rating at the rated  
voltage) because the charging current decreases as the charging  
voltage increases. In a conventional charger in which current  
25 15 is regulated to a constant value until the charging voltage rises  
to the maximum charging voltage, the power consumed by the  
circuit must increase as the voltage rises as the current is  
30 being held constant. Hence the transformer must be rated to  
provide the maximum charging current at the maximum charging  
20 voltage, rather than at the minimum charging voltage selected as  
discussed above. A transformer with a lower power rating is  
35 lighter, smaller, and less expensive and generates less heat.

As mentioned, in this specification, in many passages,  
40 25 reference will be made to the charging of a lithium-ion cell; the  
representative voltages and currents specified at various points  
in the charging circuit are for a representative such cell, and  
the charging circuit parameters for such cell will be given  
45 typical values. However, it is to be understood that there is  
30 a variability in the characteristics of commercially-manufactured  
lithium-ion cells; such variability has to be taken into account



5 in establishing various critical voltage and current values  
within the charging circuit. Further, it is to be understood  
that a given charging circuit could be designed to charge two or  
10 more lithium cells arranged in parallel or in series, and that  
5 depending upon the load for the circuit (i.e. the number of  
lithium-ion cells to be charged and whether they are connected  
in parallel or series) such values again would require adjustment  
15 from the typical values given in this specification.

10 The method according to the invention may be referred to as  
20 a "starved regulator technique" or as a "tapered current/constant  
voltage" technique. Reference to a "starved regulator" is  
appropriate because during the initial charging phase, the linear  
regulator IC device does not limit the charge voltage as the  
25 15 supply voltage is too low to require limiting. The regulator is  
starved for lack of voltage; this is not the way in which such  
regulators are designed to be used. The term "tapered  
30 current/constant voltage" is appropriate because current steadily  
diminishes as the threshold voltage is approached at which charge  
20 voltage regulation commences; charge voltage is maintained at a  
constant value during the regulated stage of the charging  
35 operation.

40 25 While the invention is optimized if the more recently  
available LDO charge-control IC device is used, the invention may  
also make use of the older generation of linear IC devices, and  
in that event entails advantages of the sort recited in the  
45 preceding description relative to previously known circuits that  
employ the older generation of linear IC devices. In each case,  
30 the conventional current-regulating subcircuit can be eliminated.

5                   Summary of the Drawings:

10                   Figure 1 is a circuit diagram of a charging circuit for a  
5                   lithium-ion cell incorporating a linear regulator subcircuits of  
the type previously known in the technology, and incorporating  
an older known type of charge control IC device.

15                   Figure 2 is a circuit diagram of a charging circuit for a  
lithium-ion cell incorporating a linear regulator subcircuit of  
20                   the type previously known in the technology, and incorporating  
a more recent known type of charge control IC device.

25                   Figure 3 is a circuit diagram of a charging circuit for a  
15                   lithium-ion cell including a charge-voltage regulator subcircuit  
in accordance with the invention, and incorporating an older  
known type of charge control IC device.

30                   Figure 4 is a circuit diagram of a charging circuit for a  
lithium-ion cell including a charge-voltage regulator subcircuit  
20                   in accordance with the invention, and incorporating a more recent  
known type of charge control IC device.

35                   Figure 5 is a graph plotting the output voltage against  
output current of a universal AC adaptor used in place of the  
40                   transformer, bridge rectifier, and smoothing capacitor of Figure  
25                   3 for the purpose of testing the circuit shown in Figure 3.

45                   Figure 6 is a graph plotting the voltage drop across and the  
current through the lithium-ion cell of Figure 1 during the  
30                   operation of the charging circuit of Figure 1.

Figure 7 is a graph plotting the voltage drop across and the current through the lithium-ion cell of Figure 3 during the operation of the charging circuit of Figure 3.

Figures 8 - 11 are graphs plotting the output voltage against output current of AC adaptors rated at 300, 400, 800, and 1200 mA, respectively, each used in place of the transformer, bridge rectifier, and smoothing capacitor of Figure 4 for the purpose of testing the circuit shown in Figure 4.

#### Detailed Description with Reference to the Drawings:

In the following, if a voltage is stated at a particular point in a circuit, it is to be understood that such voltage is measured relative to ground. In each of Figures 1 through 4, the grounds are terminals G1, G2, G3, and G4, respectively.

Figure 1 illustrates a conventional lithium-ion cell charging circuit whose elements are interconnected in accordance with known technology. An alternating-current source 101, which may typically be a mains power source at standard mains voltage (110-120 volts in North America), provides power to the input winding 103 of a transformer 105 whose secondary winding 107 delivers an AC output that is rectified by a bridge rectifier circuit 109 and is smoothed by smoothing capacitor 111. If desired, more elaborate smoothing may be provided in this conventional circuit and in the charge circuit according to the invention, to be described below. If the resulting unregulated DC current applied at a voltage  $V_{W1}$  between terminals W1 and G1 in the circuit were applied directly to lithium-ion cell 135 to be charged, there would be a serious risk of applying too high

5 a charging current or too high a charging voltage, or both, to  
the lithium-ion cell 135, risking damage to the cell 135 and  
other hazards (including serious internal gas expansion within  
10 cell 135 and potentially an explosion). Accordingly, it is  
5 conventional to provide in such charging circuit regulator  
subcircuits to control the current and voltage applied to the  
cell 135.

15  
10 If the lithium-ion cell 135 is nearly fully discharged to  
rated minimum discharge voltage when it is connected to the  
circuit of Figure 1 at terminals Z1 and G1 for recharging, there  
20 is no immediate risk of applying too high a charging voltage (the  
fully discharged condition of cell 135 precludes too high an  
initial charge voltage rise); the immediate risk is that too high  
25 a charging current might be applied. Accordingly, the linear  
current regulator subcircuit comprising charge control integrated  
circuit (IC) device 113 and resistor 119 ensures that charging  
current is kept within an acceptable range. Once the charge  
30 voltage at terminal Z1 in the circuit reaches the maximum charge  
voltage acceptable for charging the lithium ion cell 135, a  
second regulator subcircuit limits the charge voltage to hold the  
35 charge voltage at or below a preset maximum voltage.

40 25 The second regulator subcircuit (charge-voltage subcircuit)  
comprises charge control IC device 123, fixed resistor 129, and  
variable resistor 133. Fixed resistor 129 and variable resistor  
133 are used to set the regulated value of the charge voltage in  
accordance with the instructions of the manufacturer of the  
45 charge control IC device 123. Resistors 129 and 133 may normally  
30 be omitted if the IC device 123 has been designed by the  
manufacturer for the particular lithium-ion cell to be charged.

5           The charge-voltage subcircuit limits the charge-voltage to the maximum voltage for the particular lithium-ion cell to be charged.

10           5           The IC devices 113 and 123 are conventional and may each be one and the same type of device, for example, the Motorola™ model LM317 charge control IC device. The IC devices 113 and 123  
15           are connected within their respective subcircuits in conventional manner. The input terminal 115 of IC device 113 is connected to  
10           the positive output terminal W1 of the bridge rectifier 109. (Terminals W1, G1, Y1 and Z1 in the circuit may or may not be  
20           correlatable with physically discrete terminals, as the circuit designer may prefer). The output terminal 117 of IC device 113  
25           15           is connected to one terminal of resistor 119, and the other terminal of resistor 119 is connected to the adjustment input  
30           terminal 121 of IC device 113. The bridge rectifier negative terminal G1 (which may be considered a ground line for the  
                  circuit) is connected to the negative terminal of lithium-ion cell 135.

20           IC device 123 is similarly conventionally connected. The  
35           input terminal 125 of IC device 123 is connected to terminal Y1, the output terminal 127 of IC device 123 is connected at terminal  
                  Z1 to one terminal of resistor 129 whose other terminal is  
40           25           connected to the adjustment terminal 131 of IC device 123. The variable resistor 123 is connected between the adjustment  
                  terminal 131 and terminal G1. If the IC device 123 has been  
45           designed by the manufacturer as discussed above, then terminal 131 (which would then be referred to as ground terminal 131) is  
50           30           connected directly to the terminal G1; resistors 129 and 133 are omitted.

5           During the initial stage of the charging operation, the  
current regulator subcircuit comprising IC device 113 and  
resistor 119 regulates current, but IC device 123 provides an  
10           unregulated connection between its input terminal 125 and output  
5           terminal 127, since the output voltage (the charge voltage  
applied to lithium-ion cell 135) does not require regulation  
during the initial stage of the charging operation. However,  
15           when the charge voltage at terminal Y1 reaches the established  
threshold at which the maximum permitted charging voltage for  
20           application to cell 135 appears at terminal Z1 (relative to  
ground voltage at terminal G1, of course), IC device 123 begins  
to regulate the output voltage at terminal Z1, maintaining it at  
the maximum permitted charge voltage value pre-set for charging  
the cell 135. From the time that IC device 123 begins to  
25           regulate the output voltage at terminal Z1 that charges the cell  
135, the charge current applied to cell 135 begins to decline  
approximately logarithmically, and eventually approaches zero by  
the time that the cell 135 is fully charged to the capacity  
permitted by the pre-set regulated charge voltage.

20

35           Figure 2 is a charging circuit for a lithium-ion cell that  
is essentially identical to the circuit of Figure 1 except that  
charge control IC devices 213 and 223 respectively have been  
substituted for charge control IC devices 113 and 123 of Figure  
40           1. Otherwise, the circuit of Figure 2 may be identical to the  
circuit of Figure 1. The charge control IC devices 213 and 223  
of Figure 2 are the more recent "low drop-out voltage" or "LDO"  
type of IC devices capable of operating with a lower minimum  
45           differential voltage across charge control IC device 223. The  
30           IC devices 213 and 223 are conventional and may each be one and

5 the same type of device, for example, the Micrel™ model MIC29372  
charge control IC device.

10 Figure 3 illustrates a charging circuit according to the  
5 invention for a lithium-ion cell 335 that resembles, to a  
considerable extent, the charging circuit of Figure 1 but  
completely eliminates the charge current regulator subcircuit of  
15 Figure 1. In Figure 3, an alternating current source 301  
provides power to the input winding 303 of a suitable transformer  
20 305 whose secondary winding 307 provides an output AC current  
that is rectified by bridge rectifier 309, the output of which  
is smoothed by smoothing capacitor 311. The charging circuit  
illustrated in Figure 3 will also perform advantageously, at  
25 15 least for some applications, without the smoothing capacitor 311,  
but the smoothing capacitor 311 is desirable to increase the  
effective DC voltage and to correct the power factor.

30 The transformer 305 is selected not only for suitability to  
meet the usual charging circuit requirements, but also for its  
20 inherent current-limiting capability during the initial mode of  
operation of the circuit that enables the conventional current-  
35 limiting subcircuit to be eliminated. In the transformer 305,  
the windings ratio is selected to provide an output AC voltage  
that after rectification delivers a DC supply voltage across  
25 terminals W3, G3 that is sufficient to provide a regulated charge  
40 voltage at the preferred maximum pre-set value (which DC supply  
voltage may be lower than that provided in the circuit of Figure  
45 1 by at least the minimum dropout voltage of the charge control  
IC device 113), but with a voltage and current rating low enough  
30 to limit initially the charge current in the manner discussed  
below. Otherwise, circuit elements 301, 305, 309, and 311 may

5 be essentially identical to the counterpart circuit elements 101, 105, 109, and 111 of Figure 1 and are interconnected in essentially the same way.

10 5 However, in contradistinction to conventional charging circuits, the output of the bridge rectifier 309 applied across terminals W3 and G3 of Figure 3 is not regulated by any active  
15 current regulating device; instead, the circuit of Figure 3 relies upon the inherent current regulatory capability of the  
10 transformer 305 to limit charge current, as will be further discussed below.

20 Charge control IC device 323 may be identical in type to IC device 123 of Figure 1, e.g. a Motorola<sup>TM</sup> LM317 device, and is  
25 15 connected in the circuit of Figure 3 in generally the same way as IC device 123 is connected in the circuit of Figure 1. As is the case with Figure 1, as long as the charge voltage applied across the lithium-ion cell 335 remains below the designed  
30 maximum charge voltage for the circuit, charge control IC device 323 does not regulate the charge voltage, but begins to operate in regulation mode only when the charge voltage at terminal Z3  
20 has reached the designed permitted maximum value. Accordingly, to achieve this charge voltage regulation, input terminal 325 of IC device 323 is connected to the bridge rectifier output  
35 positive voltage terminal W3 (there being no intervening charge current regulator circuit), and the output terminal 327 of IC device 323 is connected to the positive terminal of lithium-ion cell 335; the connection terminal is identified as Z3. Connected  
40 25 between the output terminal 327 and the adjustment terminal 331 of IC device 323 is the resistor 329 whose resistance may be selected to be the same as that of resistor 129 of Figure 1,



5 assuming that IC device 323 is of the same type as IC device 123  
of Figure 1. Connected between the adjustment terminal 331 and  
"ground" terminal G3, which is connected to the negative terminal  
10 of lithium-ion cell 335, is an adjustable resistor 333 that can  
5 be essentially identical to adjustable resistor 133 of Figure 1,  
again assuming that IC device 323 is of the same type as IC  
device 123 of Figure 1. Resistors 329 and 333 may be omitted and  
15 terminal 331 (which would then be referred to as ground terminal  
331) connected directly to "ground" terminal G3 if the IC device  
10 323 has been designed by the manufacturer for the particular  
lithium-ion cell to be charged.  
20

Figure 4 is a charging circuit for a lithium-ion cell 435  
that is essentially identical to the charging circuit of Figure  
25 3 except that IC device 423 is of the "low drop-out voltage" or  
"LDO" type more recently available. Otherwise, the elements of  
Figure 4 are essentially identical to the counterpart elements  
30 of Figure 3. Thus AC source 401, transformer 405 having primary  
winding 403 and secondary winding 407, bridge rectifier 409 and  
20 smoothing capacitor 411 are essentially identical to the  
counterpart elements 301, 305, 309 and 311 of Figure 3, the  
35 output of the bridge rectifier 409 of Figure 4 being applied  
across terminals W4 and G4. Terminal G4 serves as ground  
terminal for the circuit and is connected to one terminal of  
40 25 adjustable resistor 433 and to the negative terminal of lithium-  
ion cell 435. Resistor 429 may be of the same resistance value  
as resistor 329 (again assuming identity of type of IC devices  
323, 423) and is connected along with adjustable resistor 433 to  
45 the adjustment terminal of IC device 423 in essentially the same  
30 manner as resistor 329 and adjustable resistor 333 are connected  
in Figure 3. The input, output and adjustment terminals of IC

5 device 423 are identified by reference numerals 425, 427, and 431  
respectively. The output voltage applied at circuit terminal Z4  
to the positive terminal of lithium-ion cell 435 is regulated by  
charge control IC device 423 in essentially the same way as the  
10 voltage at terminal Z3 is regulated by the IC device 323 of  
Figure 3, the significant difference being that the minimum  
difference between the supply voltage at terminal W4 and the  
regulated charge voltage at terminal Z4 is lower for the circuit  
of Figure 4 than for the circuit of Figure 3 because the LDO  
15 charge control IC device 423 operates at a lower dropout voltage.  
IC device 423 may be essentially identical to the IC device 223  
of Figure 2 and may be, for example, a Micrel<sup>TM</sup> model MIC 29372  
device.

25 15 The reason that the charging circuits of Figures 3 and 4 are  
able to function successfully despite the absence of a charge-  
current regulating subcircuit is that the transformer 303 or 403,  
as the case may be, is selected so that its loading effect  
30 provides an inherent current-limiting function. An understanding  
20 of this phenomenon is facilitated by reference to the graph of  
Figure 5.

35 Figure 5 is a graph of the output voltage representative of  
that of a typical power transformer of the type that would be  
25 used in the circuits shown in Figures 1 - 4 measured after  
rectification and smoothing. In Figure 3, this voltage would be  
40 measured at terminal W3. For convenience, the voltage plotted  
in Figure 5 is the measured output voltage of a 300 mA-rated  
45 universal (multi-voltage) AC power adaptor set at the 6.0 volt  
30 setting with a line voltage input of 110 volts AC and assuming  
a variable load over the range plotted, the variation in the load

5 correspondingly varying the current draw. The AC power adaptor  
includes a 300 mA-rated transformer corresponding to transformer  
303 or 403 and rectification and smoothing components equivalent  
10 to those in Figures 1 - 4. Note that the 6.0 setting indicates  
5 an output voltage of 6.0 volts DC at 300 mA with an input voltage  
of 120 volts AC rather than 110 volts AC. The lower input AC  
voltage used to obtain the data for Figure 5 resulted in a  
15 reduction in the output voltage at 300 mA current to about 5.0  
volts DC.

10  
20 As is apparent in Figure 5, the rectified and smoothed DC  
voltage provided by an unregulated DC power supply (an example  
of which is the portion of the circuit shown in Figure 3 between  
the alternating current source 301 and terminal W3 of the  
25 smoothing capacitor 311) declines with increasing current draw.  
To utilize this effect so that no charge-current regulating  
subcircuit is needed, the battery charger designer must select  
an appropriate transformer. Rectification and smoothing may be  
30 accomplished by a variety of known circuit designs. The use of  
20 designs for rectification and smoothing other than that shown in  
Figures 1 - 4 may result in a different constant voltage drop  
35 across the rectifier from that discussed below, but the rate of  
decline of voltage with increasing current will not be affected.

40 25 To select a transformer appropriate for use in a charging  
circuit for a particular lithium-ion cell or battery, the current  
rating and secondary voltage of the transformer must be  
determined. Cell/battery manufacturers generally suggest a  
45 charging rate (conventionally referred to as "C" or "C rate") for  
30 a lithium-ion cell or battery of 0.5 C to 1.0 C to obtain optimal  
cell or battery lifetime. The C rate is the value of current

5 required to provide a given charge capacity within a given time,  
and its unit is defined so that a 1.0 C rate is a rate that  
discharges the cell or battery in 1 hour. For example, the 1.0  
10 C rate for a 500mAh battery is 500 mA and a 0.5 C rate is 250 mA.  
5 A transformer current rating should preferably be selected that  
is within the 0.5 C to 1.0 C range, or at least not above the 1.0  
C rate, to obtain optimal cell or battery life and minimize  
15 transformer weight and size. (Lower C rates can be chosen, but  
these appreciably increase the required charging time). The  
10 transformer's secondary voltage at the selected current rating  
should then be selected so that the DC voltage supplied to the  
20 voltage regulator (IC device 323 in the circuit shown in Figure  
3 and voltage regulator IC device 423 in the circuit shown in  
Figure 4) is approximately equal to the sum of (1) an initial  
25 minimum charging voltage of the cell or battery to be charged  
(typically chosen as approximately 3.5 or 3.6 volts based upon  
measurements of the charging characteristics of the cell or  
30 battery to be charged) and (2) the minimum dropout voltage of the  
voltage regulator of approximately 1.8 to 2.0 volts for a typical  
20 voltage regulator IC such as the LM317 (for low dropout voltage  
regulators such as the MIC 29372 the minimum dropout voltage may  
35 be as low as approximately 0.8 volts, increasing in proportion  
to the load current). Typically the secondary voltage of the  
transformer should therefore be selected so that the DC voltage  
40 25 supplied to the voltage regulator is about 5.3 to 5.6 volts at  
the selected current rating for a voltage regulator IC such as  
the LM317. Selection of a higher secondary voltage would cause  
45 current in excess of the transformer's current rating to be drawn  
during initial charging, and selection of a lower secondary  
30 voltage would reduce the charging current.

5 To compensate for line voltage variations it is advisable  
to select the current rating of the transformer as approximately  
the 1.0 C rate and the secondary voltage of the transformer based  
10 upon the maximum expected transformer primary voltage to avoid  
5 the current exceeding the transformer rating.

Examples:

Example 1:

10 In a representative lithium-ion cell charging circuit in  
20 conformity with Figure 3, the cell 335 (an NEC Moli Energy  
Corporation IMP220748) to be charged had a nominal 3.6 volt/500  
mAh rating. A current rating of 300 mA was selected, as it is  
25 15 a readily available current rating for power transformers and is  
within the desired range for a 500 mAh cell, as discussed above.  
In testing the circuit, in place of the transformer 305, bridge  
30 rectifier 309, and smoothing capacitor 311, a 300 mA rated  
universal (multi-voltage) AC power adaptor set at the 6.0 volt  
20 setting and supplied by an AC input voltage of approximately 110  
volts was used (the same input voltage used to obtain data for  
35 the loading curve plotted in Figure 5). Hence the unregulated  
voltage/current relationship, measured across the smoothing  
capacitor 311, is as shown in Figure 5. A Motorola<sup>TM</sup> LM317  
40 25 device was chosen as the IC device 323. Resistor 329 had a  
resistance of 2 k $\Omega$  and variable resistor 333 a maximum resistance  
of 1 k $\Omega$ . In this example, the transformer 305 was selected based  
upon its current rating at 110 volts AC input. As discussed  
45 above it is preferable to use the current rating at the maximum  
30 expected line voltage, which can be as high as 132 volts AC.  
However, as the current rating selected was considerably less

5 than the 1.0 C rate (300 mA rather than 500 mA), the transformer  
selected is appropriate. The examples given below illustrate  
10 selection of transformer specifications based upon maximum line  
voltage. While the current rating for transformer selected for  
5 this example at an input of 132 volts AC and a selected voltage  
of 6.0 volts is not known, it is expected that the rating would  
be not be greater than 500 mA (maximum charging current suggested  
15 by the manufacturer).

10 As discussed above, charging occurs in two stages. In the  
first stage (before the voltage across the cell 335 reaches 4.1  
20 volts), assume that at a given time the cell 335 is partially  
charged so that the charge voltage at terminal Z3 is, for  
example, 3.5 volts. The IC device 323 is set by the resistors  
25 329 and 333 so that it will not regulate until the charge voltage  
at terminal Z3 is 4.1 volts. As IC device 323 is not regulating  
voltage, its input voltage (terminal W3) will be higher than the  
voltage at its output (terminal Z3) of 3.5 volts by its minimum  
30 dropout voltage of approximately 1.8 volts, hence the voltage at  
terminal W3 will be approximately 5.3 volts. From the loading  
20 relationship shown in Figure 5, the current drawn by the battery  
will be limited to approximately 300 mA, which is the rated  
35 current of the transformer (in this example, the rated current  
of the power adaptor).

25 As the cell 335 becomes charged, the voltage at terminal Z3  
will gradually increase until it reaches 4.1 volts and the second  
stage of the charging process begins. The voltage measured at  
45 terminal Z3 (the voltage drop from terminal Z3 to terminal G3)  
30 is the sum of the battery voltage and the voltage drop across the  
internal resistance of the battery due to the current flowing

5 through the battery. Note that the battery voltage is here  
distinguished from the voltage drop across the battery measured  
at terminal Z3. The battery voltage will be slightly less than  
10 4.1 volts (or else charging would cease as no current would flow)  
5 and the continuing charging current will be decreasing as the  
battery accepts further charge and the voltage increases toward  
4.1 volts. When the voltage at reaches 4.1 volts, the input  
15 voltage of the IC device 323 at terminal W3 will be approximately  
5.6 volts. At 5.6 volts, the transformer 305 will limit the  
10 current to approximately 200 mA, as can be seen from Figure 5.  
It can be seen that as the charge voltage increased during the  
20 first stage, the charging current gradually declined, or "tapered  
down", linearly from approximately 300 mA to approximately 200  
mA.

25 15  
During the second stage, as the battery continues to charge,  
the battery voltage approaches 4.1 volts and the current through  
30 the battery must decline as the internal resistance is fixed and  
the voltage drop across the internal resistance is the difference  
20 between the regulated voltage across the battery and the battery  
voltage. The declining current causes the voltage at terminal  
35 W3 to increase as the load on the transformer 305 is further  
reduced, but the increased voltage at terminal W3 is limited by  
the IC device 323. This increases the voltage drop across IC  
25 device 323, but the current is declining rapidly so that the  
40 power dissipated by IC device 323 decreases.

45 The behavior of the voltage measured at terminal Z3  
(labelled "E") and the current (labelled "I") passing through  
30 terminal Z3 during the charging of cell 335 discussed above is  
illustrated by the charging curves shown in Figure 7. For

example, the transition from the first to the second stage takes place at just under 4000 seconds.

Example 2:

A similar illustration of the behavior of the voltage measured at terminal Z1 (labeled "E") and the current (labelled "I") passing through terminal Z1 during the charging of cell 135 in the prior art circuit shown in Figure 1 is shown in the charging curves of Figure 6. The measurements used to plot Figure 6 were obtained by using the same 300 mA rated universal (multi-voltage) AC power adaptor that was used to obtain data for the loading curve plotted in Figure 5 except that the output voltage selector of the power adaptor was set at the 9.0 volt setting. The adaptor was supplied by an AC input voltage of 110 volts. In place of the transformer 105, the bridge rectifier 109 and the smoothing capacitor 111 shown in Figure 1 the adaptor was used.

A comparison between the charging curves shown in Figure 6 and those shown in Figure 7 suggests that the circuit shown in Figure 3, which is a battery charger in accordance with the invention, is capable of charging a lithium-ion cell in essentially the same time as the prior art charger circuit shown in Figure 1, but does so without the charge-current regulating subcircuit of Figure 1, provided that an appropriate transformer current and voltage rating are selected.

Note that the universal (multi-voltage) AC power adaptor used in the examples given above contains a multi-tap transformer and provides a selector switch for selecting a tap



5 for the desired output voltage. (Neither a designer of a  
battery charger in accordance with the prior art nor a designer  
of a battery charger in accordance with the invention would be  
likely to use a multi-tap transformer except for testing, but  
10 5 would instead select a power transformer with the desired  
current rating and a fixed voltage rating. Nevertheless, the  
choice of such multi-tap transformer for testing purposes is not  
inappropriate.)

10 Example 3:

20 As a further example, battery chargers for NEC Moli Energy  
Corporation lithium ion rechargeable batteries models IMP300648-  
1, IMP340848-1, and IMP341065 may be designed using single-  
25 15 voltage AC adaptors such models T35-4.4-300, T35-4.4-400, T35-  
4.4-800, and T35-4.4-1200 obtained from ENG Electric Co. Ltd.,  
3F No. 558, Hong Chang Twelve St., Taoyuan City, Taiwan ROC.  
Such AC adaptors contain a transformer, a bridge rectifier, and  
30 a smoothing capacitor so as to provided an unregulated DC power  
20 supply for use as a battery substitute for battery powered  
devices. Since the adaptor inherently includes a transformer  
35 (305, 405), a bridge rectifier (309, 409), and a smoothing  
capacitor (311, 411), these elements of Fig. 3 and 4 need not be  
separately provided.

40 The specifications of NEC Moli Energy Corporation lithium  
ion rechargeable batteries models IMP300648-1, IMP340848-1, and  
IMP341065 are provided in NEC documents Nos. PE2523 (Ver. 2),  
45 PE2526 (Ver. 3), PE2512 (Ver. 1), all published in April, 1999.  
30 The specifications of earlier similar models are given in  
earlier publications. Each battery is rated at a charge voltage

5 of 4.2 volts and a nominal operating voltage of 3.8 volts.  
Nominal capacities are 650 mAh, 1030 mAh, and 1650 mAh,  
respectively. For the purpose of designing a charger, the  
10 5 inventor has found that a minimum charging voltage somewhat less  
than the nominal operating voltage is desirable, although the  
exact voltage used is not critical. In this case, a minimum  
15 charging voltage of 3.6 volts is suggested by the following  
considerations. The NEC documents mentioned above show plots of  
the charging voltage as a function of time. In each case, the  
10 20 charging voltage increases almost instantly from the discharged  
voltage (which may be as low as 2.5 volts) to approximately 3.4  
volts and climbs within a short time on the order of minutes to  
roughly 3.8 volts. From there it climbs somewhat more slowly  
25 15 until it reaches the maximum charging voltage of 4.2 volts (at  
which point the charging circuit must clamp the voltage or the  
battery may be damaged). While an initial charging voltage of  
3.4 volts could be used, the inventor has found that using an  
30 initial charging voltage of 3.6 volts to select the current  
rating of the transformer does not cause the initial current to  
20 reach levels high enough to adversely affect the battery being  
charged. Because initially the current and voltage are  
35 unregulated, if it happens that a battery is charged that has  
been fully discharged and the current rating of the transformer  
used in the charger was selected to be the 1.0 C rate based upon  
40 25 3.6 volts as an initial charging voltage, the initial current  
will exceed the current rating of the transformer for a short  
period. However, the inventor has found that the 1.0 C rate is  
45 not exceeded by a significant amount for long enough to cause  
harm to the battery in such circumstances. Using a lower  
30 initial charging voltage for selecting a transformer would mean  
that a smaller transformer with a lower current rating would be

5 chosen. Doing so would reduce the current provided to the  
battery throughout the charging cycle and therefore adversely  
10 affect the charging rate. A compromise between selecting a low  
5 initial charging voltage, which would decrease the charging  
rate, and a high initial charging voltage such as 3.8 volts,  
which would increase the possibility of damage to the battery in  
the initial portion of the charging cycle (only at the maximum  
15 line voltage, of course), is to use 3.5 or 3.6 volts as the  
initial charging voltage for the purposes of designing the  
10 charger.

20 Figures 8, 9, 10, and 11 are graphs of the DC output  
voltage in volts as a function of current in milliamps for  
adaptors T35-4.4-300, T35-4.4-400, T35-4.4-800, and T35-4.4-  
25 1200, respectively, based upon input voltages of 132 volts AC.  
Input voltages of 132 volts should be used in selecting an AC  
adaptor or an equivalent transformer/bridge rectifier 307/309 or  
30 407/409 so that variations in line voltage with the normal range  
of 10% above the nominal line voltage of 120 volts AC will not  
20 cause the current at the minimum charging voltage to exceed the  
maximum charging current of the battery. If the AC adaptor is  
35 selected so that the maximum charging current for a particular  
battery at the minimum charging voltage is provided at an input  
voltage to the AC adaptor of 132 volts AC, then lower (and  
25 therefore safer) maximum charging currents will be provided at  
lower AC input voltages.

45 Example 4:

30 Applying the inventive method discussed above, an AC  
adaptor for use in a battery charger within the scope of the

invention for charging an NEC Moli Energy Corporation lithium ion rechargeable battery model IMP300648-1 (say) should be selected by finding an AC adaptor which provides a current of 650 mA or less at a voltage calculated as the sum of the 3.6 volt minimum charging voltage and dropout voltage of the linear regulator that limits the voltage across the battery (e.g., IC device 423 in Figure 4). Typically, the dropout voltage is approximately 0.6 volts for a low dropout voltage device such as the Micrel™ model MIC 29372. Hence an AC adaptor that provides 4.2 volts at a current of 650 mA or less when provided with an input voltage of 132 VAC is optimal.

Example 5:

Inspection of Figures 8 - 11 indicates that the T35-4.4-400 adaptor, whose loading curve is plotted in Figure 9, is an optimal choice for an NEC Moli Energy Corporation lithium ion rechargeable battery model IMP300648-1, assuming that a low dropout voltage device such as the Micrel™ model MIC 29372 is used as in the circuit shown in Figure 4. The T35-4.4-800 and T35-4.4-1200 adaptors would not be usable as at 4.2 volts the current provided by each exceeds 650 mA. The T35-4.4-300 adaptor could be used, but would provide less current and therefore require more time to recharge the battery.

Similarly, of the AC adaptors under discussion, the best choices for the NEC Moli Energy Corporation lithium ion rechargeable batteries models IMP340848-1 and IMP341065 can be seen to be the T35-4.4-800 and T35-4.4-1200 adaptors, respectively. However, neither provides a full 1.0C current and are hence not optimal.

5

25

20

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25

30

5  $P_d = (V_d) (I_{out}) = (1.5V) (0.3A) = 0.45W$

where

$P_d$  is the power dissipated in the IC device 323;

10  $V_d$  is the voltage drop across the IC device 323, i.e. the  
5 difference between the voltages at terminals Z3 and W3 in the  
circuit; and

15  $I_{out}$  is the charge current supplied to the cell 335.

20 In constant-voltage mode (in which the IC device 323 is  
10 in regulating mode), the maximum power dissipation of the IC  
device 323 is roughly given by:

$$P_d = (V_W - V_Z) (I_{out})$$

where

25  $V_W$  is a typical voltage at terminal W3 in the circuit  
during the constant-voltage stage; and

$V_Z$  is the voltage at terminal Z3 in the circuit.

30 Accordingly,

20  $P_d = (6.4V - 4.1V) (0.2A) = 0.46W$

35 The foregoing power dissipation losses at about 0.5 watt are  
significantly superior to power dissipation losses in the  
circuits of Figures 1 and 2, in each of which, assuming similar  
40 25 circuit implementation but necessarily involving a second charge  
control IC device in each circuit, power dissipation losses can  
easily exceed 1 watt.

45 If the circuit of Figure 4 were substituted for that of  
30 Figure 3 in the foregoing example, a further improvement in  
power dissipation losses would result; such losses in a circuit

essentially equivalent to that discussed above but with a Micrel™ model MIC 29372 LDO device 423 substituted for the Motorola™ LM317 device specified above are typically less than about 0.25 W.

#### Effect of AC Line Voltage Variations on Charging Time:

Testing of lithium ion batteries suggests that the first 80% of capacity of the battery is attained during the portion of charging before the charging voltage reaches the maximum charging voltage specified by the manufacturer. Hence if 1000 mA of charging current is applied to a 1000 mAh cell, the 80% capacity level would be attained in approximately 0.8 hours. The last 20% of capacity is attained during the constant voltage portion of charging. During that period, the battery determines the amount of current it can consume. The time the battery takes to attain the final 20% of capacity is approximately 1 hour regardless of how much charging current is available. Therefore the total time it takes to charge a 1000 mAh cell with a charging current of 1000 mA is approximately 1.8 hours. If only 500 mA of charging current is provided to a 1000mAh cell, the first 80% of capacity would take 1.6 hours and the final 20% capacity would be attained in again 1 hour. Therefore the total charging time would be 2.6 hours.

If an AC adapter is selected for which the current of the AC adapter at a charging voltage of 3.6 volts is 450 mA with 108 volts AC input, 600 mA with 120 volts AC input, and 850 mA with 132 volts AC input, then the charging time to attain 80% capacity for 108 VAC input is  $1000 \text{ mAh} \times 80\% + 450 \text{ mA} = 1.78$  hours, for 120 VAC input is  $1000 \text{ mAh} \times 80\% + 600 \text{ mA} = 1.23$

5 hours, and for 132 VAC input is  $1000 \text{ mAh} \times 80\% \div 850 \text{ mA} = 0.94$   
hours. Since the last 20% will always take approximately 1  
hour, the total times for the various input voltages are 2.78  
10 hours for 108 VAC, 2.23 hours for 120 VAC, 1.94 hours for 132  
5 VAC. For many applications this variation in charging times is  
not significant, especially in view of the reduced cost, size,  
and heat produced by a battery charge in accordance with the  
15 invention.

10 The foregoing discussion has proceeded on the basis that  
the output voltage at terminals W3 and W4 in the circuits of  
20 Figures 3 and 4 respectively is a DC voltage, but as a practical  
matter, there will continue to be some AC ripple in the voltage  
at this terminal in the respective circuit. However, the IC  
25 15 device 323 or 423 is effective to limit the charge voltage  
applied to the lithium-ion cell 335, 435 to values that do not  
damage the cell.

30 While the foregoing circuits have been described in the  
20 context of charging a lithium-ion cell, it is apparent that the  
circuits have utility whenever it is necessary to supply a  
35 charging current to a battery or the like, that during a first  
stage requires only that the charging current be below a  
specified value, and during a second stage additionally requires  
40 25 that the charging voltage be below a specified value.

Variations will occur to those skilled in the technology  
45 without involving any departure from the principles of the  
invention. For example, various other types of rectifier could  
30 be substituted for the bridge rectifier 309, 409, or various



5 more elaborate smoothing circuits could be substituted for the  
smoothing capacitor 311, 411.

10 The scope of the invention is not limited to the circuits  
5 illustrated and described but is as defined in the appended  
claims.

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## Claims

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What is claimed is:

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1. A charging circuit for charging a lithium-ion cell or battery at a charging voltage that varies during the charging of the cell or battery from a selected minimum charging voltage to a predetermined maximum charging voltage, comprising:

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(a) a selected suitable transformer for transforming AC line voltage applied to the primary winding thereof to a lower AC secondary winding voltage, the transformer being selected to limit secondary winding output current when the charging voltage is greater than the selected minimum charging voltage so that the secondary winding output current will not exceed a selected upper limit for the lithium-ion cell;

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(b) a rectifier sub-circuit connected to the secondary winding of the transformer for rectifying the secondary winding voltage; and

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(c) a charge-voltage regulator sub-circuit connected to the rectifier sub-circuit for receiving the rectified secondary winding voltage and providing an output charging voltage that is limited to the predetermined maximum charging voltage; the charge-voltage regulator sub-circuit being connectable to the lithium-ion cell or battery for charging the lithium-ion cell or battery by applying the output charging voltage across the lithium-ion cell or battery;

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the charging circuit in operation providing charging current to the cell or battery in two successive stages, viz

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5 (i) a first stage, during which the charge-voltage regulator  
sub-circuit operates in non-regulating mode thereby to apply  
output charging voltage across the lithium-ion cell or battery  
10 at a value below the predetermined maximum charging voltage, and  
charging current is limited by means of the loading effect of  
the transformer; and

15 (ii) a second stage, during which the charge-voltage regulator  
sub-circuit operates in a voltage-regulating mode thereby to  
apply output charging voltage across the lithium-ion cell or  
20 battery at a value limited to the predetermined maximum charging  
voltage.

25 2. A charging circuit as defined in Claim 1, wherein the  
charge-voltage regulator sub-circuit operates in its voltage-  
regulating mode when the voltage charging voltage across the  
lithium-ion cell or battery reaches predetermined maximum  
30 charging voltage.

35 3. A charging circuit as defined in Claim 1 or Claim 2,  
additionally comprising a smoothing sub-circuit connected  
between the rectifier sub-circuit and the charge-voltage  
regulator sub-circuit for smoothing the rectified secondary  
40 winding voltage to supplied to the charge-voltage regulator sub-  
circuit.

45 4. A charging circuit as defined in any of Claims 1 - 3,  
wherein the transformer is selected on the basis that the AC  
line voltage applied to the primary winding thereof is a  
predetermined maximum AC line voltage.

5           5. A charging circuit as defined in any of Claims 1 - 4,  
          wherein the minimum charging voltage is selected to be less than  
          the predetermined nominal voltage of the lithium-ion cell or  
10           battery and greater than the initial charging voltage of the  
          lithium-ion cell or battery when the charging current is held at  
          a constant level equal to the 1.0 C rate for the lithium-ion  
          cell or battery.

15           6. A charging circuit as defined in any of Claims 1 - 4,  
          wherein the minimum charging voltage is selected to be  
          approximately equal to the average of (1) the initial charging  
20           voltage of the lithium-ion cell or battery when the charging  
          current is held at a constant level equal to the 1.0 C rate for  
          the lithium-ion cell or battery and (2) the predetermined  
25           nominal voltage of the lithium-ion cell or battery.

30           7. A charging circuit as defined in any of Claims 1 - 4 for a  
          single lithium-ion cell, wherein the minimum charging voltage is  
          approximately 3.6 volts.

35           8. A charging circuit as defined in any of Claims 1 - 7,  
          wherein the upper current limit is selected to be not greater  
          than the maximum rate for the lithium-ion cell or battery  
          specified by the manufacturer of the lithium-ion cell or  
40           battery.

45           9. A charging circuit as defined in any of Claims 1 - 7,  
          wherein the upper current limit is selected to be not less than  
          the 0.5 C rate nor greater than the 1.0 C rate for the lithium-  
          ion cell or battery.

5 10. A charging circuit as defined in any of Claims 1 - 7,  
wherein the upper current limit is selected to be approximately  
the 1.0 C rate for the lithium-ion cell or battery.

10 11. A charging circuit as defined in any of Claims 1 - 10,  
wherein the smoothing sub-circuit is a smoothing capacitor  
connected between the positive and negative output terminals of  
15 the rectifier sub-circuit so that the rectified secondary  
winding voltage supplied by the rectifier sub-circuit is applied  
across the smoothing capacitor.

20 12. A charging circuit as defined in any of Claims 1 - 11,  
wherein the charge voltage regulator sub-circuit comprises a  
selected suitable charge-control IC device whose input terminal  
25 is connected to the positive output terminal of the rectifier  
sub-circuit, and whose output terminal is connected to the  
positive terminal of the lithium-ion cell or battery to be  
charged, and whose ground terminal is connected to the negative  
30 terminal of the rectifier sub-circuit and to the negative  
terminal of the lithium-ion cell or battery to be charged.

35 13. A charging circuit as defined in any of Claims 1 - 11,  
wherein the charge voltage regulator sub-circuit comprises a  
selected suitable charge-control IC device whose input terminal  
is connected to the positive output terminal of the rectifier  
40 sub-circuit, and whose output terminal is connected to the  
positive terminal of the lithium-ion cell or battery to be  
charged, and whose adjustment terminal is connected to one  
45 terminal of an adjustable resistor whose other terminal is  
connected to the negative terminal of the rectifier sub-circuit  
and to the negative terminal of the lithium-ion cell or battery

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5           to be charged, the adjustment terminal also being connected to  
one terminal of a resistor whose other terminal is connected to  
the output terminal of the IC device.

10          14. A charging circuit as defined in Claim 12 or Claim 13,  
wherein the charge control IC device is of the low drop-out  
voltage type.

15          15. A charging circuit as defined in any of Claims 10 - 14,  
wherein the connection between the negative output terminal of  
the rectifier sub-circuit and the negative terminal of the  
20       lithium-ion cell or battery to be charged is a direct ohmic  
connection, and the connection between the positive output  
terminal of the rectifier sub-circuit and the input terminal of  
25       the charge-control IC device is a direct ohmic connection.

30          16. A method of charging a lithium-ion cell or battery having  
a predetermined maximum charging voltage comprising a first  
stage of charging during which charging current supplied to the  
cell or battery is limited by the loading effect of a  
transformer used to supply the charging current to the cell or  
35       battery and continually declines until the charging voltage  
reaches the maximum charging voltage and a second charging stage  
commencing when the charging voltage reaches the maximum  
charging voltage during which stage the charging current is  
40       supplied to the cell or battery at the maximum charging voltage.

45          17. The method of charging a lithium-ion cell or battery as  
defined in Claim 16, wherein the transformer is selected to  
supply less than a selected maximum current at a selected  
initial charging voltage.

5 18. The method of charging a lithium-ion cell or battery as  
defined in Claim 167 wherein the transformer is selected on the  
basis that the AC line voltage applied to the primary winding  
10 thereof is a predetermined maximum AC line voltage.

15 19. The method of charging a lithium-ion cell or battery as  
defined in any of Claims 16 - 18, wherein the initial charging  
voltage is selected to be less than the predetermined nominal  
voltage of the lithium-ion cell or battery and greater than the  
initial charging voltage of the lithium-ion cell or battery when  
20 the charging current is held at a constant level equal to the  
1.0 C rate for the lithium-ion cell or battery.

25 20. The method of charging a lithium-ion cell or battery as  
defined in any of Claims 16 - 18, wherein the initial charging  
voltage is selected to be approximately equal to the average of  
(1) the initial charging voltage of the lithium-ion cell or  
battery when the charging current is held at a constant level  
30 equal to the 1.0 C rate for the lithium-ion cell or battery and  
(2) the nominal voltage of the lithium-ion cell or battery.

35 21. The method of charging a lithium-ion cell or battery as  
defined in any of Claims 16 - 18, wherein the maximum current is  
selected to be not greater than that for the lithium-ion cell or  
battery specified by the manufacturer of the lithium-ion cell or  
40 battery.

45 22. The method of charging a lithium-ion cell or battery as  
defined in any of Claims 16 - 18, wherein the maximum current is  
selected to be not less than the 0.5 C rate nor greater than the  
1.0 C rate for the lithium-ion cell or battery.



5           23. The method of charging a lithium-ion cell or battery as  
defined in any of Claims 16 - 18, wherein the maximum current is  
selected to be approximately the 1.0 C rate for the lithium-ion  
10 cell or battery.

24. A charging circuit for charging a lithium-ion cell or  
battery at a voltage not exceeding a predetermined maximum  
15 charge voltage and a current not exceeding a predetermined  
maximum charge current, comprising:

20 a transformer for transforming line voltage to a lower AC supply  
voltage and limiting the maximum charging current supplied to  
the lithium-ion cell or battery;

25 a rectifier for rectifying the AC supply voltage;

30 a smoothing capacitor for smoothing the rectified AC supply  
voltage to produce a DC supply voltage;

35 a charge-voltage regulator sub-circuit for limiting the DC  
supply voltage to the predetermined maximum charge voltage,

40 the charge-voltage regulator sub-circuit being connectable to  
the lithium-ion cell or battery for charging the lithium-ion  
cell or battery by maintaining the voltage limited DC supply  
voltage across the lithium-ion cell or battery.

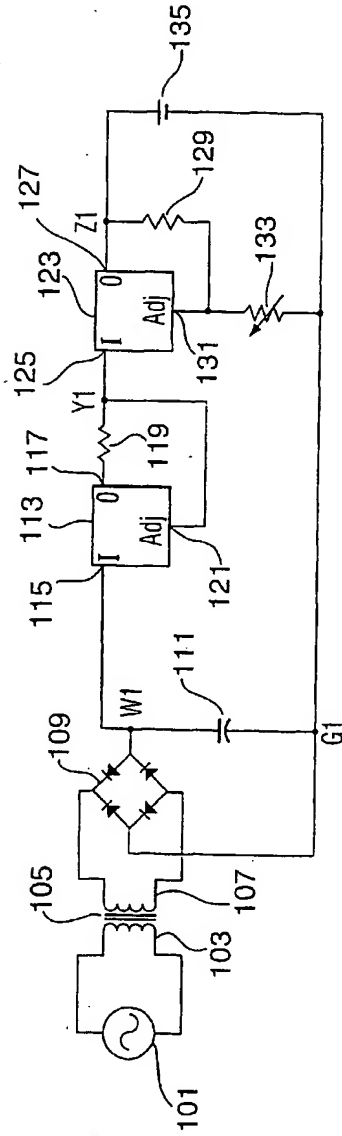


FIG. 1 PRIOR ART

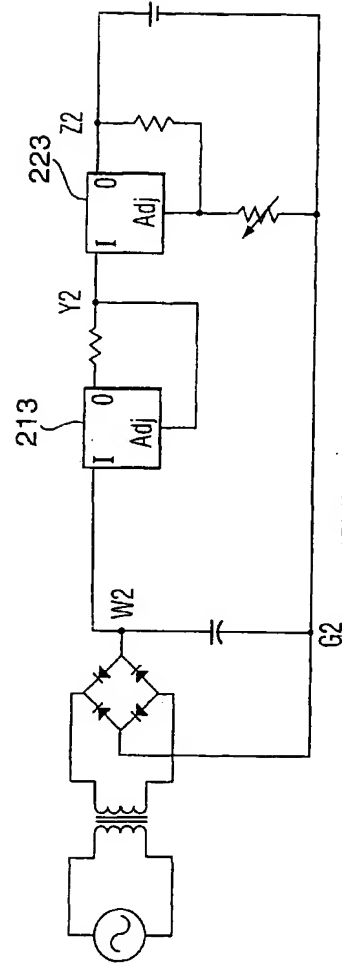
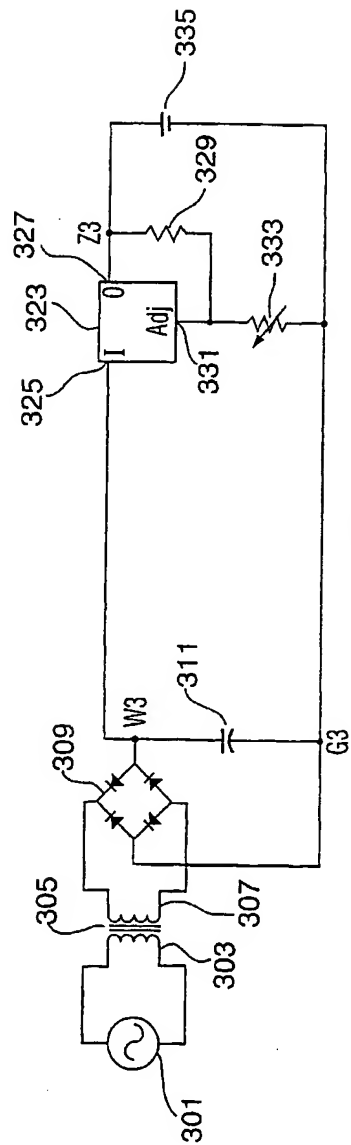
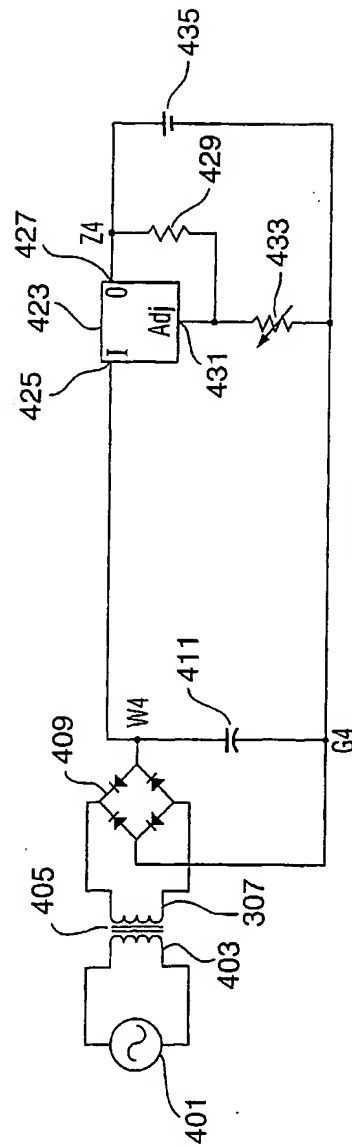


FIG. 2 PRIOR ART



**FIG. 3**



**FIG. 4**

3/5

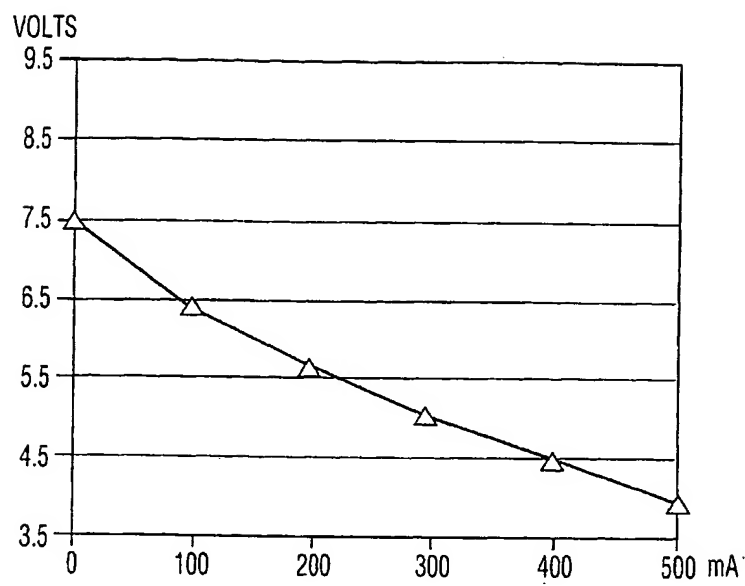


FIG. 5

4/5

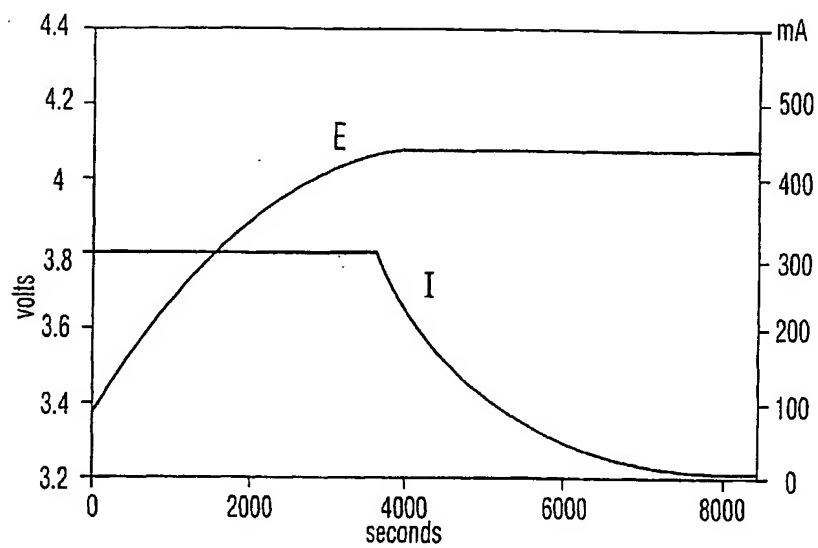


FIG. 6

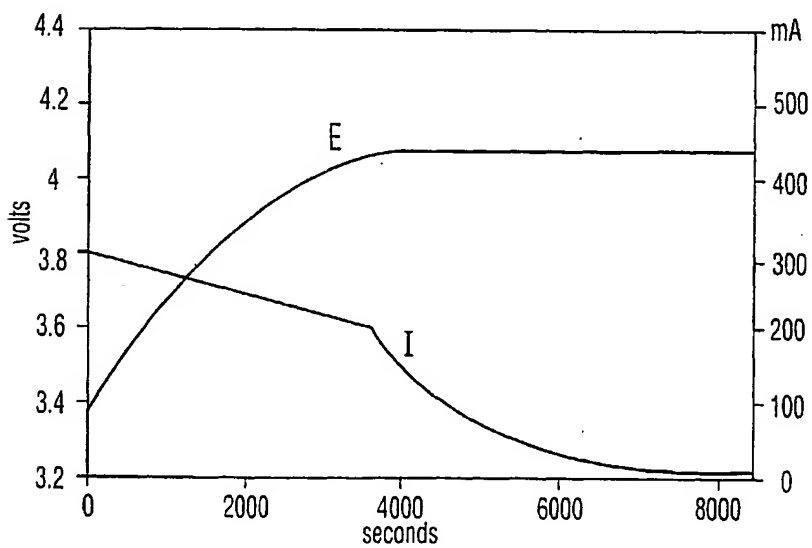


FIG. 7

5/5

FIG. 8

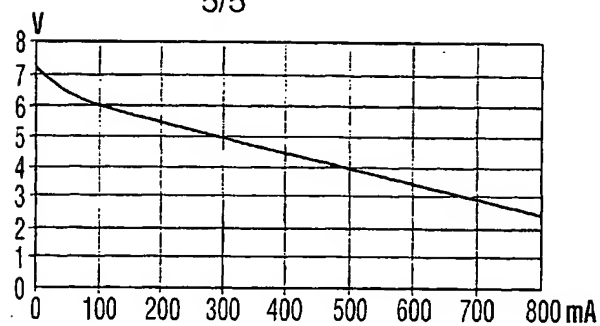


FIG. 9

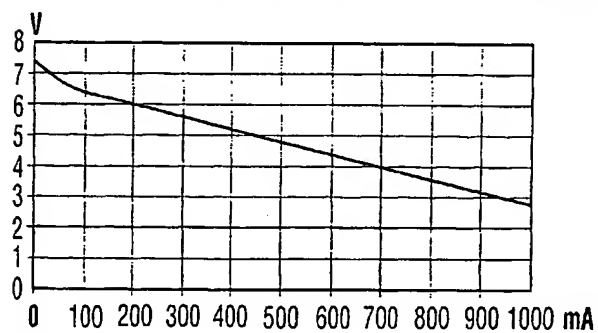


FIG. 10

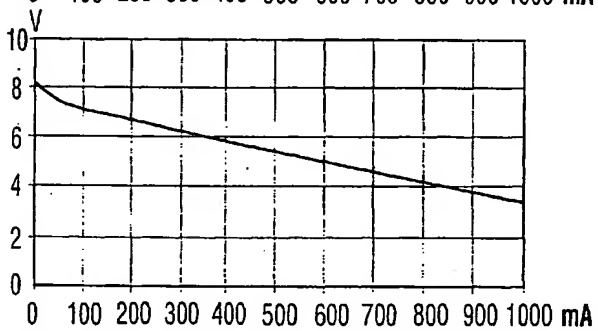
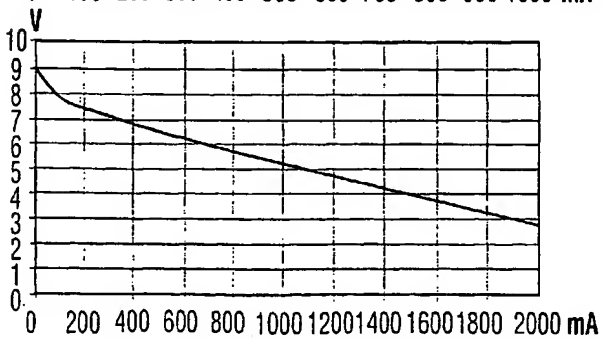


FIG. 11



# INTERNATIONAL SEARCH REPORT

International Application No.

PCT/CA 99/00805

A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 H02J7/02

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H02J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 825 699 A (BENCHMARK MICROELECTRONICS) 25 February 1998 (1998-02-25) page 2, line 54 -page 10, line 13; figures 1-11	1-3, 11, 12, 15, 16, 24
A	US 3 736 490 A (FALLON ET AL) 29 May 1973 (1973-05-29) column 3, line 30 -column 6, line 34; figures 1, 2	1, 16, 124
A	DE 35 28 476 A (GFS) 19 February 1987 (1987-02-19) the whole document	
	-/-	

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

13 December 1999

Date of mailing of the international search report

17/12/1999

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# INTERNATIONAL SEARCH REPORT

International Application No  
PCT/CA 99/00805

C. (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>PATENT ABSTRACTS OF JAPAN vol. 1996, no. 3, 29 March 1996 (1996-03-29) &amp; JP 07 296854 A (MITSUI), 10 November 1995 (1995-11-10) abstract</p>	1, 16, 24

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# INTERNATIONAL SEARCH REPORT

information on patent family members

International Application No.

PCT/CA 99/00805

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EP 825699	A	25-02-1998	NONE	
US 3736490	A	29-05-1973	NONE	
DE 3528476	A	19-02-1987	NONE	
JP 07296854	A	10-11-1995	NONE	